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14. ABSTRACT
The research has dealt with decentralized predictive sensing and control in the presence of uncertainties and constraints.

In the first part, we have adopted an information-theoretic framework based on general recursive Bayesian estimation. Each agent continuously performs Bayesian updates of the local belief while selecting the control action minimizing an information theoretic cost. Computational intractability of existing schemes with large number of agents has been addressed by partitioning the search space and proposing corresponding tailored optimization algorithms.

The second part of the research has focused on constraint satisfaction. We have studied the problem of decentralized control of a network of integrators subject to state and input linear constraints and affected by additive, set–bounded disturbances. We have introduced the notion of decentralized robust control invariant (DRCI) sets and provided a parametrization of such sets in bounds on states and control inputs. We have shown that the set of parameters leading to non-empty DRCI sets is polyhedral, and thus decentralized, constrained robust control design is a convex optimization problem. We have also addressed the problem of averaging the state of each network element and proposed an asymptotically stabilizing algorithm which is non–iterative and does not require centralized design procedure.

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A FRAMEWORK FOR INFORMATION THEORETIC COOPERATIVE SENSING AND PREDICTIVE CONTROL

FA9950-9-2-02060
Final Report

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Abstract

The research has dealt with decentralized predictive sensing and control in the presence of uncertainties and constraints.

In the first part, we have adopted an information-theoretic framework based on general recursive Bayesian estimation. Each agent continuously performs Bayesian updates of the local belief while selecting the control action minimizing an information theoretic cost. Computational intractability of existing schemes with large number of agents has been addressed by partitioning the search space and proposing corresponding tailored optimization algorithms.

The second part of the research has focused on constraint satisfaction. We have studied the problem of decentralized control of a network of integrators subject to state and input linear constraints and affected by additive, set–bounded disturbances. We have introduced the notion of decentralized robust control invariant (DRCI) sets and provided a parametrization of such sets in bounds on states and control inputs. We have shown that the set of parameters leading to non-empty DRCI sets is polyhedral, and thus decentralized, constrained robust control design is a convex optimization problem. We have also addressed the problem of averaging the state of each network element and proposed an asymptotically stabilizing algorithm which is non–iterative and does not require centralized design procedure.

1 Status/Progress

The report is a final summary of the project's results at its completion date.

In its most general formulation, the research project has dealt with the problem of predictive sensing and decentralized cooperative control in the presence of uncertainties and

constraints on states and inputs of the controlled dynamical systems. We approached the topics of the project separately by considering two independent problems: (i) the problem of active sensing for search and localization tasks posed in the framework of recursive Bayesian estimation, and (ii) the general problem of decentralized control of uncertain, constrained dynamical systems. We summarize research activities and findings for each of these two problems.

1.1 Bayesian Decision Making for Search-and-Localization Tasks

As a research framework, we considered a team of agents whose common goal is to detect and track a number of targets in a cluttered and uncertain environment. The autonomous control problem for searching-and-localization (SAL) tasks can be posed as follows: Given initial information regarding the presence or location of target, position sensor(s) such that the presence or absence of a target can be determined, and if the target is found to be present, localize it with precision suitable for other mission objectives, such as following, refueling or rescue. There are two fundamental elements to this problem: means of estimating the state of the targets, and a cooperative control scheme that allows the agents to act autonomously upon such estimates. We adopt a standard information-theoretic framework for the management of the sensors based on general recursive Bayesian estimation. More specifically, each of the agents continuously performs Bayesian updates of its local belief based on local sensing and the information received from other agents, while selecting the control action which would reduce uncertainty in the local belief. This is valuated by an information-theoretic measure (e.g. the information entropy of the belief or divergence of the successive beliefs).

We first focused on one target and proposed a technique for reconfiguring the search space in order to accommodate the dynamic nature of moving targets. In [P2] it is shown that the PDF values in the search space can be *computed exactly*, using only computation over the search space.

We next focused on addressing the computational intractability of existing schemes (cf. [1,3,4]) when applied to a large number of agents and multiple targets. In [P5] we proposed a framework which deals with a probabilistic number of targets within a geographic area. The area is first partitioned into distinct search and track regions. Then, task allocation is used to assign the best vehicle to each region by minimizing an information theoretic cost function. In [P6] we exploit the task allocation problem structure in order to formulate a nonlinear optimization problem, which can be then solved efficiently by using a tailored optimization algorithm.

1.2 Decentralized Robust Control for a Network of Integrators

The second part of the research activities has been devoted to the generic problem of decentralized control of linear dynamical systems in the presence of disturbances and hard constraints on the systems' states and control inputs.

We considered a scenario in which the systems are coupled through constraints and dynamics. The goal was to control a large network of linearly constrained, dynamically coupled systems subject to additive, set–bounded disturbances. The problem is approached using

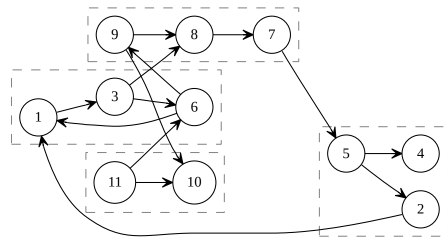

Figure 1: Example network.

set–theoretic methods, in particular the formalism of robust control invariance [2]. We have investigated two closely related problems. Problem 1: from which set of initial states $\mathscr{X}_0$ can one robustly control the system? Problem 2: how does one design a decentralized control law which satisfies state and inputs constraints and guarantees convergence for all the initial states in $\mathscr{X}_0$?

For both problem (1) and (2) the research has focused on networks of integrators.

- **Problem 1.**
  We have shown that a the maximal robust control invariant (RCI) set for a network of integrators is finitely characterized and introduced a *notion of decentralized RCI sets* [P1,P3]. To the best of our knowledge, this is the first attempt to define and compute decentralized invariants in our field. We introduced a parametrization of such sets in the bounds that define state and control constraints. Finally, using the specific form of the considered constraints and the basic property of the RCI sets for a network of integrators, we were able to show that the problem of selection of constraint parameters for which a non–empty decentralized RCI set for a network of integrators exists can be formulated as an optimization problem subject to linear constraints.

  Computational benefits in robust control synthesis are visible already in a small example. Consider the network of integrators defined by the graph shown in Figure 1. The flow over edges and the states of each integrator are bounded. The dynamics of each node is affected by an additive bounded, persistent disturbance. The set of control inputs (feasible flows) $\mathscr{F}$ for the *centralized design* for the given network is 11-dimensional polyhedron defined by 360 (non-redundant) inequalities. On the other hand, local sets of feasible flows for the decentralized design $\tilde{\mathscr{F}}^{\mathscr{S}_1}$, $\tilde{\mathscr{F}}^{\mathscr{S}_2}$, $\tilde{\mathscr{F}}^{\mathscr{S}_3}$ and $\tilde{\mathscr{F}}^{\mathscr{S}_4}$ corresponding to each of the 4 groups of nodes are defined by 14, 12, 12 and 6 inequalities, respectively.

  Numerical values for the example and other details are given in the report [P3].

- **Problem 2.**
  We have addressed the problem of averaging the state of each network element [P4]. The particularity of this problem compared to standard consensus–based averaging is that the elements exchange not only the information but also the stored resource. Thus the elements are controlled–coupled through the flow constraints. A distributed algorithm for flow control has been proposed. The algorithm is non–iterative and does not require centralized design procedure. The proposed scheme guarantees state and inputs constraints satisfaction, and asymptotic convergence of states of all nodes to the same value, equal to the average of initial values. We compare our algorithm to

the distributed averaging scheme reported in the literature, based on linear policies. The simple example next shows the effectiveness of the developed control methodology. We consider the network used as an example in [5], consisting of 8 nodes and 17 edges whose graph is depicted in Figure 2.

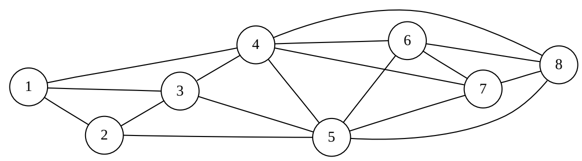

Figure 2: Graph of the network used in the numerical example.

The performance of our distributed algorithm is compared to the linear averaging (FDLA) algorithm in [5]. Time evolution of the states and flow values generated by the proposed Algorithm are depicted on the left column of Figure 3. Performance of the unconstrained linear averaging (FDLA) algorithm is shown in the central column of Figure 3. Finally, we computed the gains for the FDLA algorithm with capacity constraints and show the results in the right column of Figure 3.

Figure 3 clearly shows that the proposed control design methodology, which in general induces non–linear averaging control laws, provides practically the same performance as the fastest linear distributed averaging algorithm, while generating flows which satisfy capacity constraints. On the other hand, the original FDLA algorithm as presented in [5] generates flows which do not conform to the existing capacity constraints. If we introduce capacity constraints in the computation of FDLA gains, the performance of the linear algorithm expectedly deteriorates.

- **Application to Electrical Batteries** The lithium ion cells of an electrical battery can be seen as the storage elements of a large scale network. Electric vehicles batteries can have hundreds of cells. The control problem consists of moving charge between the cells in order to balance the battery despite disturbances events (charging and discharging events). Here balancing means that all cells have equal charge. Balancing improves the effective storage capacity and the reliability of a lithium ion battery pack. Imbalancing is induced by a variety of causes, including temperature differentials and different cells properties.

  Balancing is today achieved in production by discharging every cell to the lowest one of the battery back. This clearly leads to a waste of precious stored energy. Our idea is to connect individual cells together to form a network and use the developed methodologies for moving the charge between cells in order to balance the battery network despite disturbances. Together with Ford Research Laboratories we have been performing preliminary and very encouraging simulation tests.

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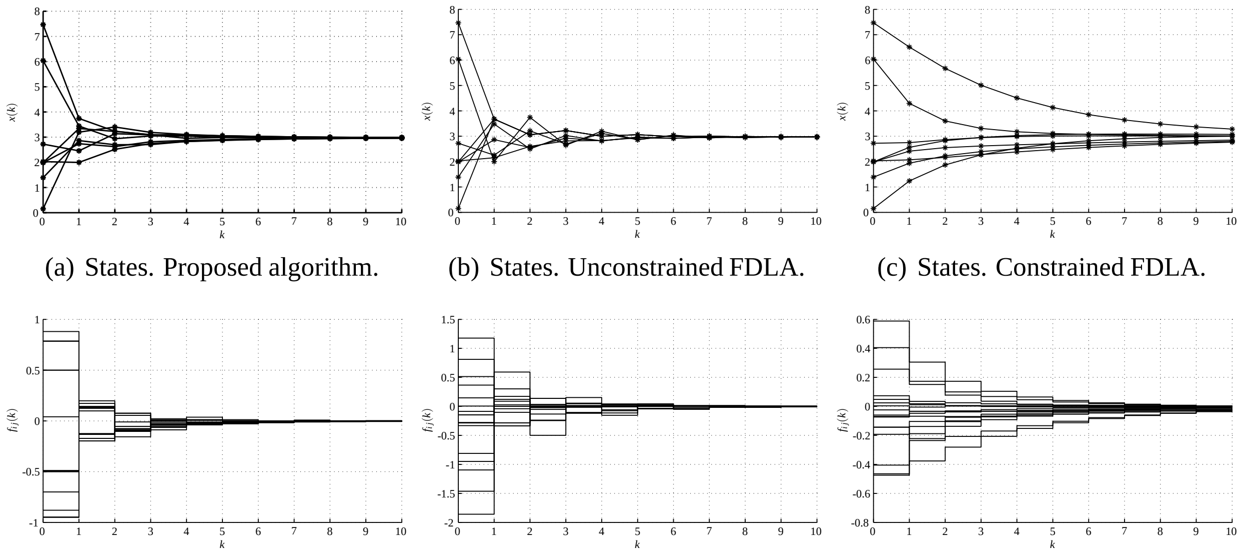

(a) States. Proposed algorithm. (b) States. Unconstrained FDLA. (c) States. Constrained FDLA.

(d) Generated flows. Proposed algorithm. (e) Flows. Unconstrained FDLA. (f) Flows. Constrained FDLA.

Figure 3: Time evolution of states and flows comparison between the proposed Algorithm and the FDLA algorithm in [5].

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Publications

P1 Miroslav Barić and Francesco Borelli, Decentralized Robust Control Invariance for a Network of Integrators, *Proceeding of American Control Conference (2010) - ACC'10*, June 2010, Baltimore, MD, USA.

P2 Benjamin Lavis, Miroslav Barić, Francesco Borrelli, Mark Godwin, and J. Karl Hedrick. Beyesian decision making for autonomous control of search–and–localization tasks. Technical report, University of California, Berkeley, Dept. of Mechanical Engineering, 2010. availble from `http://www.mpc.berkeley.edu`.

P3 Miroslav Barić and Francesco Borrelli. Decentralized Robust Control Invariance for a Network of Storage Devices. Technical report, UC Berkeley, 2011. Accepted for publication on the IEEE Transaction of Automatic Control, available from `http://www.mpc.berkeley.edu`.

P4 Miroslav Barić and Francesco Borelli, Distributed Averaging with Flow Constraints, *Proceeding of American Control Conference (2011) - ACC'11*, June 2011, San Francisco, CA, USA.

P5 Jared Wood and J. Karl Hedrick, Space Partitioning and Classification for Multi-target Search and Tracking by Heterogeneous Unmanned Aerial System Teams, *Proceedings of AIAA Infotech@Aerospace*, March 2011.

P6 Mark F. Godwin and J. Karl Hedrick, Stochastic Approximation of an Online Multiagent Routing Problem for Autonomous Aircraft, *Proceedings of AIAA Infotech@Aerospace*, March 2011.

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Transitions

Together with the Ford Research Laboratories in Dearborn, MI, USA we are investigating the potential transition of the developed methodologies to the problem of balancing electrical batteries in passenger vehicles. Approach, goals and methodologies to be shared during the transition are subject of ongoing discussions.